RECENT AND PROJECTED CHANGES IN DEAD SEA LEVEL AND EFFECTS ON MINERAL PRODUCTION FROM THE SEA

U.S. GEOLOGICAL SURVEY

Open-File Report 78-176

Prepared in cooperation with the

U.S. AGENCY FOR INTERNATIONAL DEVELOPMENT

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By

Stanley P. Sauer

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RECENT AND PROJECTED CHANGES IN DEAD SEA LEVEL AND EFFECTS ON MINERAL PRODUCTION FROM THE SEA

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ABSTRACT

Hydrologic data for the Dead Sea area were reviewed to assess the probable magnitude and rate of change of the water level of the Dead Sea. Historical average annual Dead Sea levels range from a minimum of 399.4 meters below sea level in about 1818 to a maximum of 388.6 meters below in 1896. Present levels are rapidly approaching the historical low. There is a close correlation between Dead Sea level and accumulated departure from the mean of long-term rainfall except for the most recent period since 1964. During that period rainfall has been near the long-term average but water levels have continued to decline, in part due to abstractions for irrigation in the Jordan River basin.

The dissolved-solids concentration of Dead Sea water presently is approximately 322,000 milligrams per liter and is generally well mixed throughout. This concentration is at the saturation level, resulting in continuous precipitation of some salts. The increase in dissolved solids to the present high concentration has resulted in an evaporation rate less than that estimated in previous reports. Evaporation rate from the North Basin is estimated at 1,310 millimeters per year at present. The evaporation rate from the South Basin was not

estimated due to extensive existing or planned modifications for mineral production facilities.

Water budget computations were performed at various inflow rates in order to project water-level changes for 50 years. Computations assumed closure of the South Basin by existing and proposed mineral extraction facilities. The projected 50-year changes ranged from a decline of 51 meters with no inflow from any sources to a rise of 10.2 meters when average annual inflow from the Jordan River was 750 cubic hectometers. An average annual inflow to the Sea of 900 cubic hectometers from all sources is required to stabilize the Sea at the present level. Principal impact of declining water levels on proposed potash production facilities in Jordan would be an increase in power requirements.

A cursory review of a proposed plan to divert water from the Mediterranean Sea into the Dead Sea to generate electric power and stabilize water levels indicates a very limited impact on chemical, physical, and ecological characteristics of the Dead Sea in the near future. Water-budget computations indicate that if all but 200 cubic hectometers of tributaries' waters were utilized for irrigation and other purposes, a maximum diversion of 700 cubic hectometers per year into the Dead Sea would be possible without significantly raising long-term average water levels.

INTRODUCTION

The Agency for International Development (AID) has had an active program of support for the development of countries in the Middle East for some time. Present supporting programs include the development of additional irrigated lands on the east bench of the Jordan River in Jordan and the development of potash and other mineral production facilities at the south end of the Dead Sea. A general location map is shown in figure 1. The Jordan Valley Authority, Hashemite Kingdom of Jordan, has the responsibility for all developments in the Jordanian portion of the Jordan Valley. The development of additional irrigated lands requires extensive construction of distribution facilities as well as upstream storage facilities. The development of storage and irrigation facilities in the Jordan River basin may have significant effects upon the flow in the Jordan River. Changes in Jordan River flow would result in changes in levels of the Dead Sea, which may in turn effect proposed mineral production facilities at the south end of the Dead Sea.

The level of the Dead Sea has been declining in recent years. In view of recent and potential future changes in the level of the Dead Sea, the AID entered into a Participating Agency Service Agreement with the Geological Survey (USGS) in July 1977 to secure the technical services of a USGS hydrologist to collect and analyze available hydrological data concerning the Dead Sea area in an effort to develop additional information about the water-level changes and its effect on the ecology, and potash and other mineral production in the Dead Sea region. Specifically, the duties and responsibilities of the

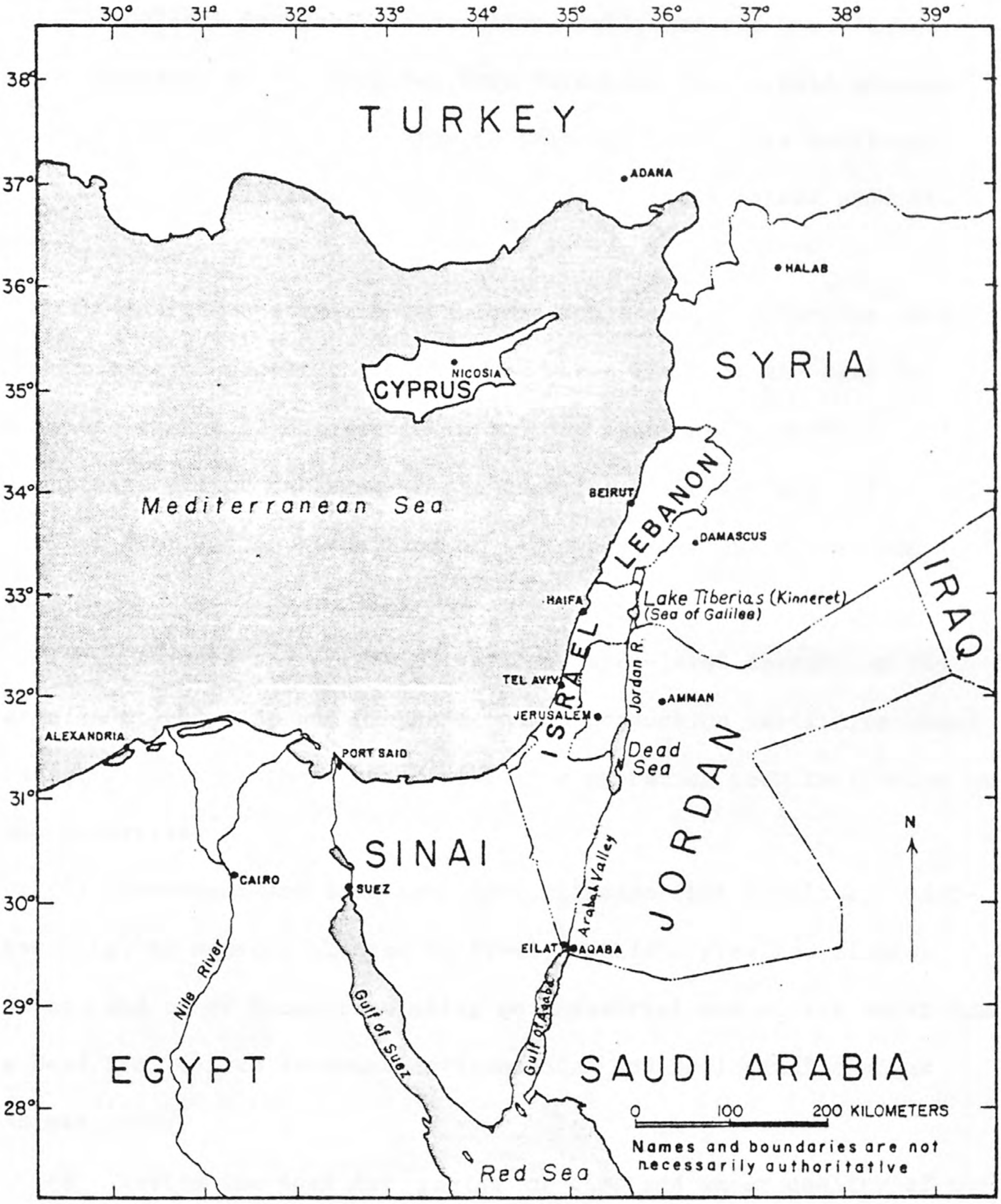

Figure 1.--Regional setting of the Dead Sea.

USGS were to:

(1) Collect available information, published and unpublished, on the hydrology of the Dead Sea from Jordanian and Israeli sources.

(2) Visit the Dead Sea area to help understand its hydrology, to collect reconnaissance type data, and to see the potash production facilities.

(3) Analyze the available information to: (a) determine rate and magnitude of recent changes of the water level of the Dead Sea and relate change to changes in inflow, at least qualitatively; and (b) estimate effect on level of the Dead Sea of no surface inflow, no inflow from Jordan River, and of inflows at various rates from Jordan River.

(4) Estimate the effect of various water-level changes on the operation of existing and proposed potash production facilities based on discussions with those responsible for operating such facilities and other expertise.

(5) Recommend any long term investigation that should be undertaken: (a) to measure changes in level, specific gravity, mineral content, and other factors relating to industrial use of the water from the Dead Sea; (b) to document environmental and ecological changes that may occur.

(6) Review the need for gaging of flow and water quality of the Jordan River in the reach between Lake Tiberias and the Dead Sea. If needed, recommend suitable location(s) for the gaging station(s).

(7) Review a recent Israeli plan to divert water from the Mediterranean Sea to the Dead Sea and comment on this plan with respect to its effects on the ecology of the Dead Sea and the surrounding land.

(8) Provide AID with a report on the results of the investigation.

The author spent two and one-half weeks in Jordan and one and one-half weeks in Israel gathering information from various sources. One week was spent in Washington, D.C., consulting with AID personnel and reviewing information in the AID and USGS headquarters office files.

A listing of published and unpublished reports and articles reviewed for the study is given in the SELECTED REFERENCES section of this report. In addition to the reports and articles listed, information was obtained from the files of various government agencies and private firms in Jordan and Israel and from discussions with personnel in these agencies and/or firms. The agencies and firms visited included:

U.S. - AID Mission, Amman, Jordan

Hashemite Kingdom of Jordan (HKJ) Agencies:

Jordan Valley Authority - Amman

Natural Resources Authority - Amman

Ministry of Communications - Amman

Arab Potash Co. - Amman and at site of proposed potash production facilities near the south end of the Dead Sea

American Embassy, Tel Aviv, Israel

State of Israel Agencies:

Meteorological Service - Tel Aviv

Water Commission - Tel Aviv

Hydrological Service - Jerusalem

Geological Service - Jerusalem

TAHAL Water Planning for Israel, LTD., Tel Aviv

Dead Sea Works, Sedom, Israel

All personnel contacted at these agencies were most helpful in providing information and assistance. Special thanks are due to Tom Pearson and Aied Sweis of the AID Mission, Jordan, Omar Abdullah and Munther Haddadin, Director and Assistant Director, respectively of the Jordan Valley Authority, Abu Ajamieh, Jordan Natural Resources Authority, Abd-Enour Habbibeh, Assistant Director, Arab Potash Company, David Neev, Geological Survey of Israel, Yaakov Vardi, Vice Presieent, Tahal, Limited, David El-Bashan, Israel Meteorological Service, and Ari Ben-Zwi, Israel Hydrological Service.

PHYSIOGRAPHY OF THE DEAD SEA REGION

Much has been written regarding the physiography of the Dead Sea region. An excellent description of physical and chemical characteristics of the Dead Sea is presented in a detailed study by Neev and Emery (1967). This section is drawn largely from that paper, supplemented by information in other references listed. All elevations shown are referenced to mean sea level, Mediterranean Sea, Survey of Israel datum.

The Dead Sea, a drainage sink with no outlet, occupies a depression near the center of a long, narrow tectonic valley (graben), extending about 600 kilometers (km) north-northeast from its juncture with the Red Sea (fig. 1). Valley width ranges from 10 to 20 km. There are four distinct segments of the valley. The Dead Sea lies in a segment beginning about 35 km south of the Sea and extending about 250 km northward through the Jordan Valley and Lake Tiberias (also referred to to as Lake Kinneret and the Sea of Galilee).

Most of the Dead Sea-Jordan Valley-Lake Tiberias segment is characterized by barren, dissected plains at several topographic levels, -175 meters (m) at the southern end, -300 m near the Dead Sea, and -200 m near Lake Tiberias. These plains are apparently remnants of the late Pleistocene Lisan Lake. The Dead Sea and Lake Tiberias occupy separate depressions in this floor. The Dead Sea is a highly saline body of water, with dissolved solids concentration exceeding 300,000 milligrams per liter (mg/L). It is about 80 km long by 18 km wide, with the surface near -400 m in 1977, and has a maximum depth of approximately 400 m.

The border escarpments consist of fault scarps or steep monoclines, marked by cliffs or steep slopes on either side, the steepest slopes being on the western side. The western border is characterized by sharp cliffs and narrow, steep canyons. The differences in slope are due to differences in lithology; the western side being composed of resistant limestone and dolomites of Cenomanian and Turonian age; the eastern side being composed of softer Nubian Sandstone of Paleozoic to Middle Cretaceous age. Elevation of the border escarpments ranges up to slightly over 1,000 m in the vicinity of the Dead Sea. Both border escarpments are mantled by more than 30 horizontal shore terraces or relic gravel bars at various elevations from current surface level up to about -180 m.

The Dead Sea consists of two distinct basins, referred to as the South Basin and North Basin, as shown in figure 2. The Lisan Peninsula will extend to the west bank when the level of the Sea reaches approximately -403 m.

The South Basin has the shape of a shallow, flat-bottomed, irregular saucer with its maximum present depth about 3 m. Total surface area is about 220 square kilometers (km^2) at elevation -400 m, or about 24 percent of the total Dead Sea area of 910 km^2. It should be borne in mind that existing developments by the Dead Sea Works, Ltd., in the Israeli portion of the South Basin, along with proposed development by the Arab Potash Co. in the Jordanian portion of the South Basin, will virtually eliminate this area as an integral part of the Dead Sea. The South Basin will be diked to establish evaporating pans for the production of potash and other minerals.

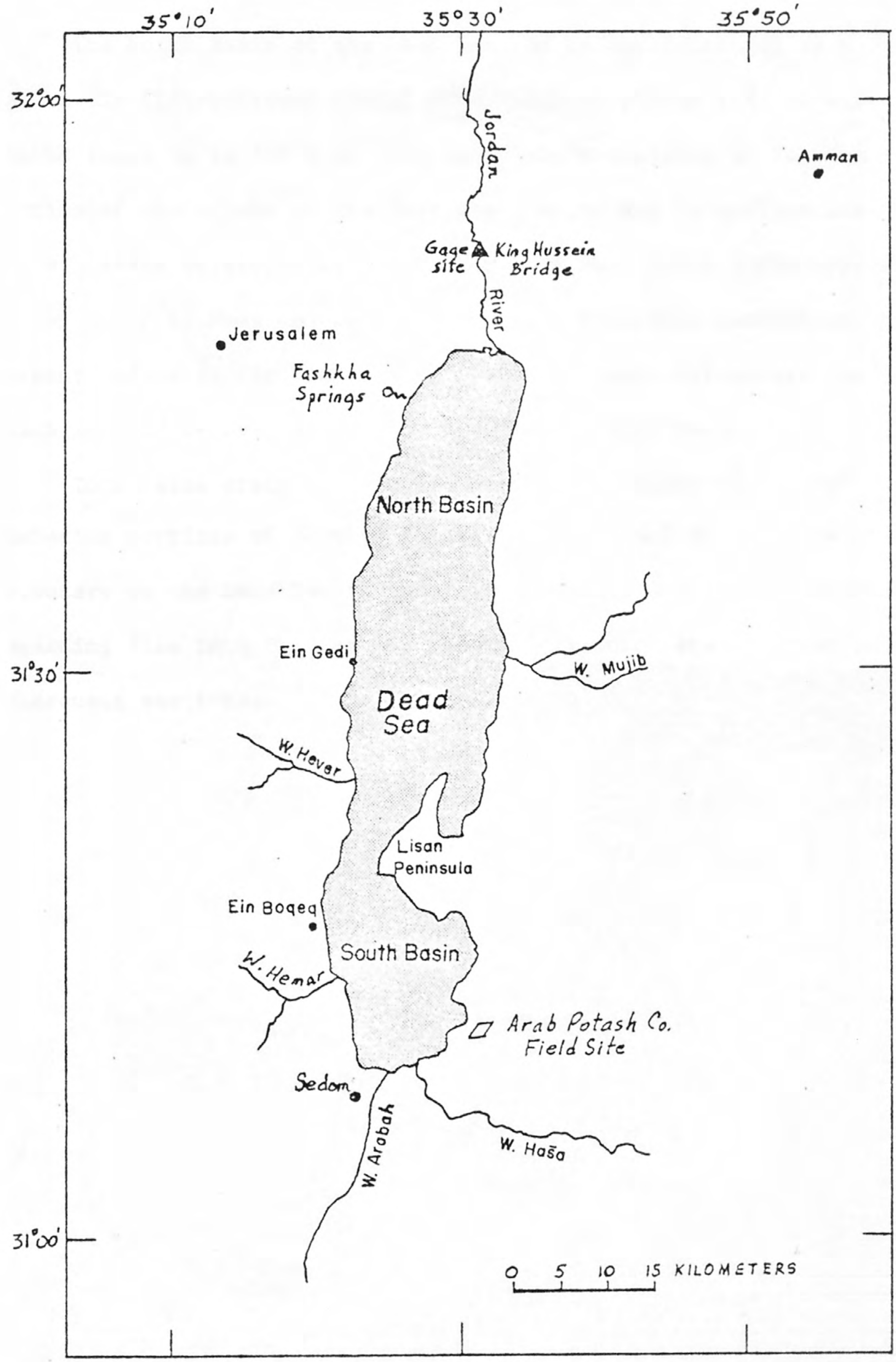

Figure 2.--Sketch map of Dead Sea area.

The North Basin of the Dead Sea can be characterized as a long, relatively flat-bottomed trough with abruptly rising side slopes. Depths range up to 400 m in this Basin which contains by far the major portion of the volume of the Dead Sea. According to surface area and volume tables developed by the author from very small scale hypsometric curves given by Neev and Emery (1967), under natural conditions, the present volume of the Dead Sea is about 137 cubic kilometers (km^3), of which 135 km^3 or over 98 percent are in the North Basin.

Total area draining into the Dead Sea is about 40,000 km^2, including portions of Jordan, Israel, Lebanon, and Syria. The principal tributary to the Dead Sea is the Jordan River. Additional information regarding flow into the Sea and general climatic data is given in subsequent sections.

CHEMICAL AND PHYSICAL CHARACTERISTICS OF DEAD SEA WATER

The chemical and physical characteristics of the Dead Sea are unusual in many respects. The dissolved-solids content is among the highest known for large bodies of water (Langbein, 1961). It is this high dissolved-solids content that provides a very valuable resource for the two countries bordering the Sea for the production of minerals, particularly potash. There are numerous articles describing the physical and chemical characteristics of the Dead Sea. A selected number of these articles in chronological sequence include Kaefoed and Hangaard (1912), Novomeysky (1936), Chemical Construction Company of New York (1954), Amiran and Karmon (1964), and Neev and Emery (1967). Each of these articles provides information on the Dead Sea waters in various degrees of detail. It may be assumed that accuracy has been improved chronologically as measurement techniques and equipment have improved. Most reports indicate salinity at depths greater than approximately 100 m is at saturation level for some salts. Salinity increases very gradually below that depth.

The most detailed and recent report is the one by Neev and Emery (1967). An intensive survey of that portion of the Sea within the boundaries of Israel as of that date was conducted by them in 1959 and 1960. The information is assumed to apply to the entire Sea. They report on the vertical distribution of temperature, density, and salinity in the North Basin as follows:

1. Temperature - seasonal fluctuation between 19°C and 35.0°C occurs in the upper 40 m. No seasonal variation below 40 m. Temperature increased gradually from between 19°C and 20°C at 40 m to 21.7°C at 150 m and was isothermal below that depth.
2. Density varies from 1.204 grams per cubic centimeter (g/cm^3) at the surface to 1.206 g/cm^3 at about 40 m depth, then increases to 1.234 g/cm^3 at 100 m depth and below.
3. Salinity increases from 288,000 mg/L in the upper 40 m to 324,000 mg/L at 100 m below the surface, with very little increase below that depth.

From the descriptions above, it is apparent that three zones should be considered: (1) a surface zone consisting of approximately the upper 40 m of water, affected by runoff, evaporation, solar heating, and other factors that vary seasonally, (2) a transition zone between 40 m and 100 m depth which is marked by an increase in density and salinity, and (3) the deep zone below 100 m where temperature, density, and salinity remain nearly constant. In the deep zone, the dissolved solids content is at saturation level for some salts and some precipitation occurs continuously. This description is similar in all prior accounts referenced, except for slight differences in absolute values and a general increase with time in surface salinity and density.

Although the three zones described in the various references have apparently existed from the time of the first observation of the Dead Sea through 1967, considerable evidence indicates that most of the Sea is now well mixed, with very little stratification of density and salinity. From personal discussions with officials of the Arab Potash Company and their consultants, and of the Geological Survey of Israel, the upper portions of the Sea are now also at or near saturation level for some salts the year round. This would indicate surface zone salinities exceeding 320,000 mg/L with a density in excess of 1.23 g/cm^3.

The total quantity of dissolved solids in the Dead Sea weighs approximately 43.8 x 10^{12} kilograms (kg), according to Neev and Emery (1967), and represents about 15 percent of the total volume of the Sea or roughly 20 km^3. They estimate the average salinity for the Dead Sea of 322,000 mg/L. The average distribution for the different ions is reported by them as:

Ion	Concentration (mg/L)	Total quantity (kg x 10^{12})
Calcium, Ca^{++}	16,860	2.30
Magnesium, Mg^{++}	40,650	5.54
Sodium, Na^{+}	39,150	5.33
Potassium, K^{+}	7,260	.99
Chloride, Cl^{-}	212,400	28.92
Bromide, Br^{-}	5,120	.69
Sulphate, $SO_4^{=}$	470	.06
Bicarbonate, HCO_3^{-}	220	.03

This distribution should be valid at this time.

HYDROLOGY OF THE DEAD SEA

Climate

The climate of the Dead Sea area is characterized by a relatively wet, cool winter season usually lasting from November through March and a hot, dry season for the remainder of the year. Temperatures occasionally drop below freezing in the highlands adjacent to the Dead Sea; however, frost is virtually unknown on the floor of the valley. Maximum summertime temperatures occasionally exceed 50°C. Most of the area in the vicinity of the Dead Sea is arid, with a marked decrease in precipitation from west to east. Precipitation increases with elevation.

The primary climatic influence is the Mediterranean Sea, the source of essentially all moisture for the area. Precipitation occurs due to orographic effects as the moisture laden winds move from west to east across the area. Annual precipitation in the Dead Sea basin ranges from approximately 1,500 millimeters (mm) on the headwaters of the Jordan River to less than 50 mm in the valley south of the Dead Sea. Due to high temperatures, low relative humidity, and large amounts of solar radiation, evaporation and evapotranspiration rates are very high, with potential evapotranspiration greatly exceeding the available supply except during some of the winter months.

Historical Sea Levels

There is ample historical evidence indicating large fluctuations in the water level of the Dead Sea and its predecessor, Lake Lisan. Paleolimnology is described to varying degrees in Neev and Emery (1967), Bender (1974), Neev and Emery (1966), and Neev and Hall (1977). Variation in water levels is ascribed to various causes, primarily variations in climate. The references coauthored by Neev provide descriptions of paleoclimate dating back about 100,000 years.

For the purpose of this investigation only variations over a much shorter time frame are of interest. The most detailed documentation of the fluctuations in Dead Sea level since the beginning of the 19th century is given in Klein (1965). The report is based on an extended investigation of all available information, including photographs, morphological indicators, travelogues, and measurements. Using information provided in that report and in a report by Jacobs International (1976), and using readings furnished by the Israel Hydrological Service and the Arab Potash Company, a graph of average annual water levels for the period 1800 - 1977 was constructed and is shown in figure 3. For convenience, calendar years and hydrologic years (October 1 - September 30) were used interchangeably. A limited study indicated very little difference in the two values.

Several conclusions may be drawn from figure 3. Lowest average annual water-surface elevation during this 177-year period occurred in about 1816-20, at elevation -399.4 m. Present water levels

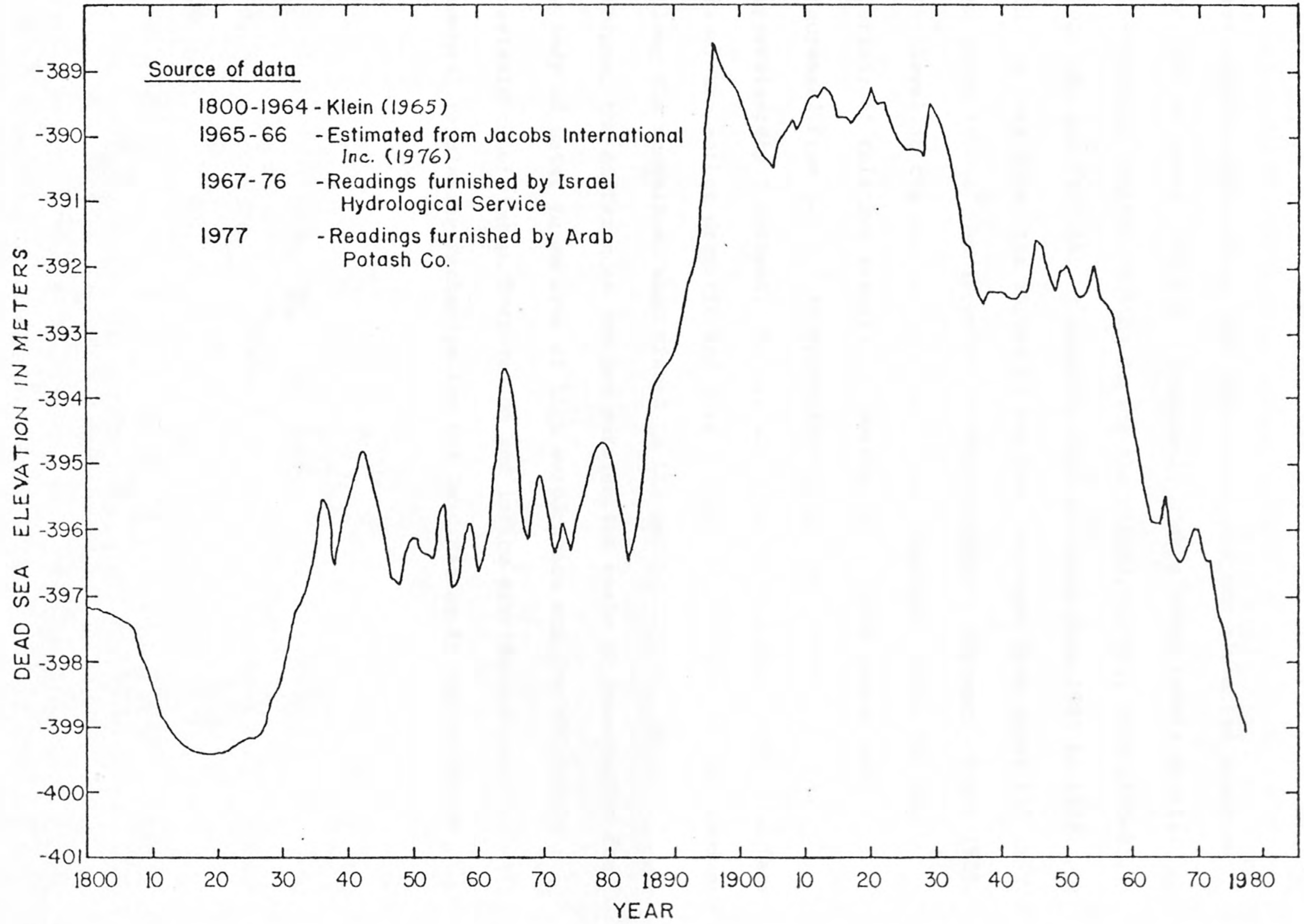

Figure 3.--Average annual elevation of the Dead Sea, 1800-1977.

are rapidly approaching that elevation. Maximum elevation occurred in 1896 at about -388.6 m. Relatively stable water levels existed for various lengths of time during the period, notably from 1835-85, 1905-29, and 1937-55. A dramatic rise occurred from 1883 to 1896. During this time, the volume of the Sea increased from about 139 km^3, to about 145 km^3, an increase of approximately 4 percent. Since 1929, the level of the Sea has declined fairly steadily except for two periods of relative stability. During the past 48 years, volume decreased from 144 km^3 to approximately 137 km^3, a reduction of approximately 5 percent. Hence, although the changes in water surface level are rather dramatic and have a significant impact on developments along the shoreline, when viewed in the perspective of changes in volume, the differences are not outside the realm of expectation for a body of water in an area of high evaporation and low but highly variable runoff rates. Evaporation and inflow provide the only natural regulating mechanism for the Dead Sea as it has no outlet.

Rainfall

Annual rainfall in the region is highly variable. Virtually all precipitation falls during the wet season from November through March. The coefficient of variation of annual rainfall for most long-term stations in the area averages about 0.34 (34 percent). This implies that in at least one-third of the years, rainfall will deviate from the long-term average by 34 percent or more. This information is taken from a publication of the Israel Meteorological Service (1967) as well as from computations performed on data provided in the Jordanian Ministry of Communications annual climatological data summaries.

There is a considerable amount of rainfall information available for the area. Crawford (1968) reviewed the rain gage network for Jordan. A review of Climatological Data Summaries for Israel indicates adequate network coverage for that country. There are two long-term rainfall stations in the immediate vicinity of the Dead Sea, Jerusalem and Amman.

Records for Jerusalem extend back to 1846. The records for Jerusalem were compared and adjusted to a single location for a period of 100 years by Rosenan (1955). This information, along with subsequent information furnished by the Israel Meteolological Service, was used to prepare a graph of accumulated departure from the long-term mean, shown in figure 4. The average precipitation for the period 1847 through 1975 was 549 mm. The graph indicates generally above average rainfall prior to 1911 and generally deficient rainfall since that time. These general trends are interrupted by periods of varying lengths.

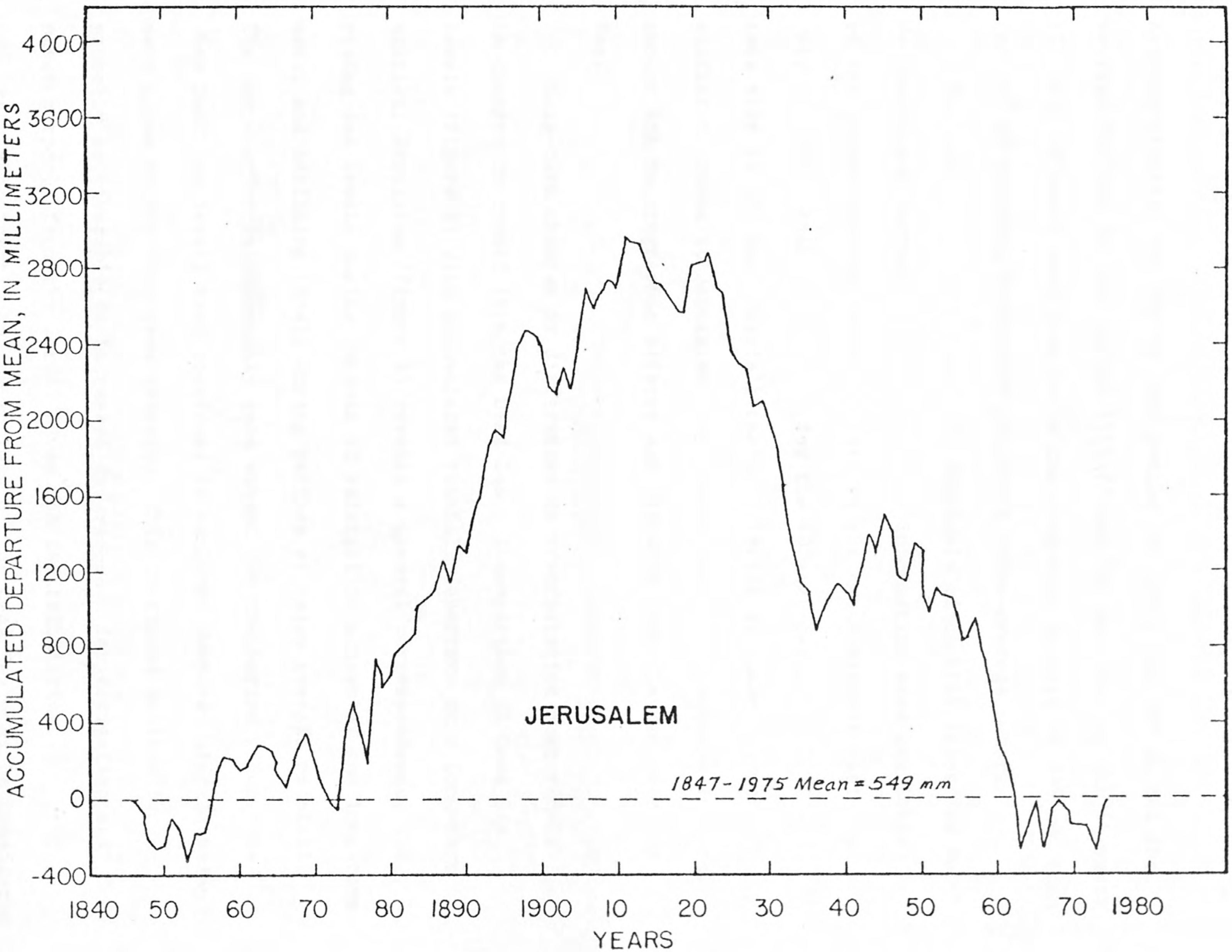

Figure 4.--Accumulated departure from mean annual rainfall at Jerusalem.

Average rainfall for the 65 year period 1847-1911 was 595 mm, and the average for the 64-year period 1912-75 was 502 mm. During the 64 years 1912-75, 43 years have been below the long-term average of 549 mm. Long periods of rainfall deficiency result in below-average runoff.

Rainfall records at Amman are available since 1923, according to MacDonald and Partners (1965); however, information made available to the author included rainfall data at the Amman airport dating back only to 1938. Average rainfall for the 40 year period 1938-77 at this site is 278 mm. Rainfall characteristics at Amman are very similar to those at Jerusalem, with a corresponding decrease in total amount due to orographic effects and distance from the Mediterranean Sea.

Long-term changes or differences in precipitation must result in changes in runoff into the Dead Sea. A comparison of Dead Sea levels (figure 3) with accumulated rainfall departure at a long-term station, Jerusalem (figure 4) reveals a general correspondence, i.e., rising sea levels during periods of rainfall in excess of the long-term mean, and declining levels during periods of below average rainfall. The correlation is remarkably good except for the period since 1964 when Dead Sea levels have continued to decline despite rainfall being very close to the long-term average. This continued decline is probably attributable to increased diversions for irrigation and other purposes from the Jordan River and its tributaries.

Rainfall directly on the surface of the Dead Sea must be considered in any water budget studies of the Sea. The standard climatological period 1931-60 was used in determining average annual rainfall on the Sea. Maps prepared by the Israel Meteorological Service and by the Central Water Authority of Jordan (responsibilities now assumed by the Natural Resources Authority, HKJ) were used. The maps prepared by the two agencies differ slightly and values were therefore averaged. Based on this information, the average annual rainfall on the surface of the South Basin is 60 mm; on the North Basin, 80 mm.

Evaporation

Evaporation rates in the vicinity of the Dead Sea are very high. Pan evaporation data are available for a number of sites in both Jordan and Israel. Several different types of evaporation pans are used, creating a problem in comparing rates for various sites. From best available data from Jordanian and Israeli sources, the average annual Class "A" pan evaporation at the southern end of the Dead Sea is approximately 3.8 m. An evaluation of available data indicates a comparable value of approximately 3.4 m at the northern end of the Dead Sea. Evaluation is difficult at the northern end as several different types of evaporation pans were used.

These rates are for evaporation of fresh water; rates for water with significant quantities of dissolved solids are somewhat less. As salinity increases, evaporation decreases and water temperatures rise at approximately the following rates, according to Harbeck (1955, p. 5):

Table 1.--Variation of evaporation ratio and temperature rise with evaporation rate and salinity.

Salinity, in milligrams per liter	Evaporation rate, in millimeters per day	Temperature rise of saline water above that of fresh water, in degrees centigrade	Ratio of saline water evaporation to that of fresh water
100,000	2	0.5	0.93
	4	.5	.94
	8	.6	.94
	16	.7	.95
200,000	2	1.2	.82
	4	1.5	.84
	8	1.6	.85
	16	1.7	.86
250,000	2	1.7	.74
	4	2.0	.77
	8	2.2	.79
	16	2.3	.81
300,000	2	2.2	.66
	4	2.6	.70
	8	2.9	.72
	16	3.1	.74
350,000	2	2.7	.57
	4	3.2	.62
	8	3.7	.65
	16	3.9	.67

The data given above were taken, in part, from extensions of curves given in Harbeck's figure 2 (1955).

There are several scientifically acceptable procedures available to estimate evaporation from a large body of water such as the Dead Sea. The most commonly used method is to collect Class "A" pan evaporation data and apply a "pan coefficient" to compute lake evaporation data. Pan coefficients for annual data generally are assumed to range from 0.6 to 0.7. However, in a comparative study of evaporation measurement techniques for data from the Salton Sea in California, U.S.A, Hughes (1967, p. 170) found a pan coefficient of about 0.50 to apply during a one-year study period based on energy- and water-budget method computations. The Salton Sea has considerably different characteristics from the Dead Sea, being much shallower and having a dissolved solids content of 35,000 mg/L compared to over 300,000 mg/L for the Dead Sea, however, the climates of the two areas are very similar. For the period of study by Hughes, pan evaporation was approximately 3.6 m per year.

The energy-budget method of estimating evaporation from a body of water is the most accurate procedure to use providing all relevant parameters can be accurately measured. According to Anderson (1954) the energy budget equation applied to a body of water may be expressed as:

$$Q_s - Q_r - Q_b - Q_h - Q_e = Q_{st} - Q_v \qquad (1)$$

where Q_s = solar radiation incident to water surface

Q_r = reflected solar radiation

Q_b = net energy lost by body of water through the exchange of long-wave radiation between the atmosphere and body of water

Q_h = energy conducted from body of water to atmosphere as sensible heat

Q_e = energy utilized for evaporation

Q_{st} = increase in energy stored in body of water

Q_v = net energy advected into body of water

This equation assumes the principle of conservation of energy but neglects items of small magnitude, such as heat transformed from kinetic energy, heating due to chemical and biological processes, and conduction through the bottom.

A detailed study of the energy and water balances for the Dead Sea was conducted by Neumann (1958). Neumann estimated average annual evaporation to be 1,470 mm from the North Basin of the Sea, 1,800 mm from the South Basin, and an average of 1,550 mm for the Sea as a whole. The computations were based on observations of meteorological data, an average water temperature of 25°C, and densities in grams per cubic centimeter of 1.195 (salinity 272,000 mg/L) for the northern Basin and 1.21 (salinity 294,000 mg/L) for the southern basin. These estimates are the most accurate available, with no other information to indicate they should not be used. If average annual pan evaporation near the Sea is assumed to be 3,600 mm, a pan coefficient of 0.59 would be required (plus adjustment factor of 0.73 for effect of salinity) to arrive at the value of 1,550 mm for Dead Sea evaporation. This coefficient appears reasonable and the values given by Neumann will be used for further computations with appropriate adjustments for changes in salinity.

Surface Runoff into Sea

Surface runoff into the Dead Sea has been estimated by a number of different investigators, with slightly different results depending upon sources of data and length of records available. In the water budget study by Neumann (1958) total surface inflow into the Sea was estimated to be about 1,490 cubic hectometers (hm^3--equivalent to million cubic meters) per year, of which 1,250 hm^3 was from the Jordan River at the King Hussein Bridge (formerly Allenby Bridge) gaging station. The gaging station is approximately 17 km above the mouth. In an early study by Novomeysky (1936) the flow of the Jordan River was estimated to be 2,370 hm^3 per year (6.5 hm^3 daily average), which represented 75 percent of the total inflow into the sea. A detailed technical analysis by Jacobs International, Inc. (1976) estimated average annual inflow to the Sea (exclusive of existing and planned diversions) to be 1,165 hm^3 from the Jordan River, 220 hm^3 from the tributaries on the eastern side of the Sea, and 140 hm^3 from the tributaries on the western side of the Sea, for a total of 1,525 hm^3.

In addition to the reference cited above, all available data from Jordanian and Israeli sources were reviewed in order to reestimate runoff into the Sea. Sources reviewed were Ben-Zwi (1977), Central Water Authority (1964), Goldschmidt (1955), Harza Overseas Engineering Co. (1977), Ionides (1939), Jordan Valley Commission (1975), MacDonald and Partners (1965), MacDonald and Partners, and Hunting Technical Services (1973), annual reports of streamflow in Jordan and Israel, and the files of the Israel Hydrological Service and the Natural

Resources Authority of Jordan. Streamflow data are available for the Jordan River at King Hussein Bridge for the period 1933 through 1966 water years, with records not published for 1960, 1961, and 1962. Unfortunately, no information on the flow of the Jordan River is available since 1966 due to the stream now being a hostile border. For the 31 years of published record, average annual flow was 987 hm^3, with a standard deviation of 336 hm^3 representing a coefficient of variation of 0.34.

There are streamflow stations on most major tributaries to the Jordan River on the eastern side. Very little streamflow data are available for western side Jordan River tributaries. In addition, records of diversions from streams in the Jordan River basin are very incomplete. It is therefore virtually impossible to accurately reconstruct the flows of the Jordan River into the Dead Sea. This is unfortunate as the Jordan River historically has contributed approximately 75 percent of the flow into the Sea. It is probable that the annual flow of the Jordan River now averages considerably less than the average of nearly 1,000 hm^3 computed from available records.

Streamflow records dating from the early 1960's as well as measurements and observations made from time to time for various reports, are available for the major wadis tributary to the eastern shore of the Dead Sea. Previous reports reviewed indicate total flow into the Sea from the eastern wadis is approximately 195 hm^3. However, streamflow records collected since 1963 indicate that this figure should be adjusted downward to 185 hm^3. In addition to this inflow, an estimated 25 hm^3 is derived from miscellaneous springs and other seepage on the eastern side. This 25 hm^3 includes ground-water contribution below the surface of the Dead Sea. Thus, a total inflow to the Sea from the east would be about 210 hm^3 as an annual average.

Streamflow information for the streams draining directly into the Dead Sea from the west is very limited. The tributaries drain areas with very little potential for agricultural development. Runoff in this area is very low. Average annual rainfall ranges from less than 100 mm to slightly over 600 mm. Little effort has been made to systematically collect runoff information. Flow was measured on the Wadi Heman, a tributary to the South Basin of the Dead Sea, for the six water years 1967 through 1972. Average flow from the 330 km^2 drainage area was measured as 1.0 hm^3 per year. Some data are available on spring flows on the western side, most notable being the Fashkha Springs near the northern end of the Sea. Average flow for this complex of springs is about 15 hm^3. The report by Jacobs International (1976) estimated a total inflow from the west to be 140 hm^3, of which only 20 hm^3 was from flood runoff, the remainder from baseflow springs and seepage including ground-water contribution below the surface of the sea. Based on available information, this appears to be a reasonable estimate.

Ground-Water Inflow

A water budget study of the Dead Sea requires an evaluation of the inflow below the surface. For some bodies of water, this can be an important consideration. A number of investigations were reviewed, including Bender (1974), Hirzalla (1973, Neumann (1958), Parker (1969), and Tleel (1963). The studies generally indicate that the ground-water gradient is toward the Sea, with steep gradients near the Sea corresponding to the surface topography. The flows are considered to be small due to the relatively low permeabilities of the aquifers. In view of these low permeabilities, the limited potential for ground-water recharge, and the absence of very large springs on either side of the Sea, it is highly unlikely that significant amounts of ground water flow into the Sea below the surface. In the detailed water budget study of the Dead Sea by Neumann (1958), ground-water inflow to the Sea was estimated to be at most on the order of 10 hm^3 per year. There is no clear evidence in the reports cited herein to indicate otherwise. The flow into the Sea below the surface is included in the estimates of springflow and seepage given in the previous section.

PROJECTED CHANGES IN DEAD SEA LEVELS

One purpose of this study was to estimate the effect on level of the Dead Sea of the following inflow conditions: no surface inflow, no inflow from Jordan River, and inflow from Jordan River at various rates. A water budget analysis for the Dead Sea was performed for these conditions in order to project changes in levels for a 50-year period.

The computations were made using the area and volume curves for the Dead Sea shown in figure 5, using the surface-area curve adjusted for closure of the South Basin. This is based on visual observation of closure on the Israeli side for evaporation pans for the Dead Sea Works and the projected facilities to be constructed by the Arab Potash Company. These existing and proposed facilities will for all practical purposes close off the South Basin. The amount of water that will be evaporated from this area will then be dependent on operations at these two facilities. The diversions by these two facilities were not used in the computations. A minimum of approximately 8.3 hm^3 must be pumped for each 100,000 metric tons of potash produced. Present diversions for mineral production are probably on the order of 15 hm^3, but may be higher.

Other assumptions used in the water budget computations include:

1. Average annual rainfall on the surface of the Sea is 80 mm.
2. Average annual inflow from all surface and underground sources other than the Jordan River is 350 hm^3.
3. Starting level for computations is - 399.0 m.
4. Initial dissolved solids concentration of the Sea is 322,000 mg/L, with no stratification. The dissolved solids concentration increases to approximately 336,000 mg/L at water surface elevation -407.0 m and below.

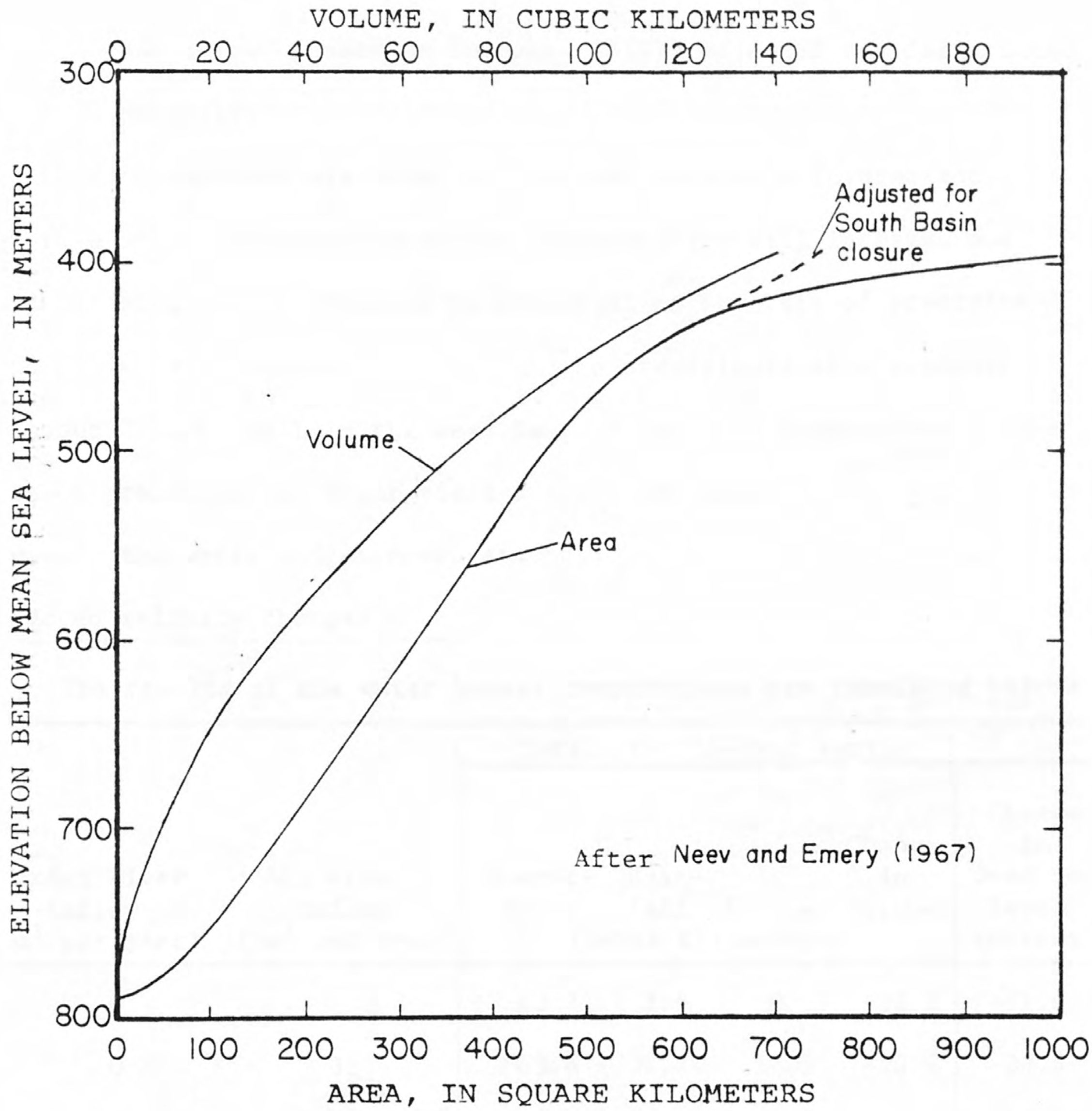

Figure 5.--Hypsometric curves for the Dead Sea

5. Evaporation from the water surface is 1,310 mm per year at elevation -399.0, decreasing to 1,270 mm per year at elevation -407.0 and below (based on Neumann, 1958), adjusted for differences in salinity.

The assumptions are based on the best available information. The rate at which dissolved-solids concentration will increase due to decreasing volume of water is dependent on the rate of precipitation of salts. Some salts will begin to precipitate at a concentration of about 322,000 mg/L in the Dead Sea. A detailed computation of the rate of precipitation might yield a different value than those assumed; however, the water budget computations would not be greatly affected by expected salinity changes.

The results of the water budget computations are tabulated below:

Jordan River inflow (hm^3 per year)	All other inflow (hm^3 per year)	Totals for 50-year period: Evaporation (cubic kilometers)	Rainfall (cubic kilometers)	Inflow (cubic kilometers)	Change in volume (cubic kilometers)	Change in Dead Sea level (meters)
0	0	40.7	2.5	0	-38.2	-51.0
0	350	43.6	2.7	17.5	-23.4	-29.6
250	350	45.2	2.9	30.0	-12.3	-15.4
500	350	47.5	3.0	42.5	-2.5	-2.5
550	350	48.0	3.0	45.0	0	0
750	350	49.5	3.0	55.0	+8.5	+10.2

From this table, it is evident that approximately 900 km^3 per year of inflow is required to stabilize the water level of the North Basin Dead Sea at -399.0 m. Periods that significantly deviate from this 900 hm average inflow would result in vatiations in the average level of the Sea.

Under natural conditions, the Dead Sea is a self regulating system. As water levels rise above about -403.0 m, the area of the Sea increases tremendously due to flooding of the South Basin. As a result, total evaporation increases significantly. As the level of the Sea declines to the point that water is confined to the North Basin, surface area and the resultant evaporation decrease by 25 percent or more. In addition, evaporation decreases as the dissolved solids concentration increases. This natural regulation pattern has been altered by reduction of the area of the South Basin for development of mineral extraction facilities and by extensive diversions of inflow for irrigation and other purposes.

EFFECTS OF SEA LEVEL CHANGES ON POTASH PRODUCTION FROM DEAD SEA

The design of mineral production facilities such as those proposed for the Arab Potash Company at the south end of the Dead Sea, requires consideration of the variation of the water level in the North Basin. Ample protection must be provided to avoid flooding of facilities due to rising water levels. Additionally, the location of intake facilities and power requirements to pump water from the Dead Sea into the evaporation pan is dependent on water levels.

Discussions with Arab Potash Company officials indicate that the intake for pumping facilities is to be located on the northern side of the Lisan Peninsula in an area of very steep bottom slope. Those discussions indicate ample provision has been made to protect facilities against rising sea levels. It is evident that the site selected is such that the principal effect of declining water levels on operations of potash production facilities would be increased power requirements. The amount of increase in power requirements will depend on the rate of withdrawal and the total decline in water level. Economic impact in turn will be dependent on cost of power. Computation of costs for various alternatives of potash production and sea level decline is outside the scope of this report.

COMMENTS ON EFFECTS OF DIVERSIONS

OF MEDITERRANEAN SEA WATER TO THE DEAD SEA

Proposals to utilize the nearly 400 m difference in elevation between the Mediterranean Sea and the Dead Sea for power production by diverting water from the Mediterranean Sea date back to near the turn of the century. Many different alternatives have been proposed from time to time. Proposals were generally considered to be technically feasible but lacking in an adequate benefit-cost ratio. A proposal is now being brought forth again with the idea of replacing water diverted for irrigation and other purposes from the Jordan River and other tributaries with Mediterranean Sea water in order to produce power and stabilize the level of the Dead Sea.

The introduction of Mediterranean Sea water into the Dead Sea would have some impact on the chemical and physical characteristics of the Dead Sea. These effects would require a long time to become apparent. There has been some discussion of diverting 1,000 hm^3 per year into the Dead Sea. Because this represents only about 0.7 percent of the current volume of the Dead Sea, changes would occur over a long period. When the water budget computations of changes in Sea level due to various inflow rates are considered, it is apparent that 1,000 hm^3 per year could not be diverted to the Dead Sea without causing rapid rises in water level, as the South Basin would not be operating as an integral unit of the Sea. From these computations, if all available tributary inflow were utilized for irrigation and other purposes (assuming an average of 200 hm^3 would not be available for use), the maximum amount of water that could be imported from the Mediterranean Sea would be on the order of 700 hm^3 per year, if long-term average water levels are to remain stable at the present elevation. This would represent approximately 0.5 percent of the volume of the Sea. Changes in chemical and physical characteristics of the Dead Sea water would therefore be minimal for the foreseeable future.

The very high salinity levels of the Dead Sea largely inhibit biological activity in the sea; life is apparently limited to low-level organisms. Because the present level of biological activity is so low, the introduction of Mediterranean Sea water would have no appreciable effect on the ecological characteristics of the Dead Sea.

RECOMMENDATIONS FOR ADDITIONAL STUDIES

Analyses presented in this report are based on information obtained from a number of sources. Data collection in the area has been seriously inhibited by political considerations. Data have been collected in Israel and Jordan for specific purposes with no coordination between the two countries. The situation was considerably worsened by the 1967 war and resultant territorial changes. As a result, very little in the way of synoptic hydrologic information exists for many factors that affect the Dead Sea.

The Dead Sea is a valuable resource for both Israel and Jordan. There are many developments, in existence as well as planned, that will affect both the levels of the Dead Sea and its chemical and physical characteristics. Projections have been made regarding these effects using less than sufficient information.

The Dead Sea is hydrologically unique in many respects. It presents an excellent opportunity for research in evaporation processes and in the depositional characteristics of large bodies of water with very high concentrations of dissolved solids. It also presents an opportunity to analyze the long-term impacts of various development activities.

It is strongly recommended that a research effort be undertaken to accurately define the various factors comprising the water and dissolved solids budget for the Dead Sea. This would entail an investigation of at least 3 to 5 years to measure and analyze evaporation. water temperature, solar radiation, wind movement, dissolved-solids concentration, rainfall on the sea surface, inflow to the sea from surface and underground sources, and dissolved solids input to the sea.

The gaging of streamflow and water quality of the Jordan River is a very important part of any assessment of the impact of upstream developments on the runoff into the Dead Sea. It is highly desirable that the station at the King Hussein Bridge be reestablished and operated indefinitely. Data collected should include both water quality and streamflow. This station provides an index of hydrologic changes in the Jordan River basin and, as a long-term station, trends can be assessed by data collected at this site. Both of these functions require the collection of suitable supplemental data in the basin upstream from the gage site in order to properly evaluate and analyze the streamflow data collected at the side. In view of its importance to all parties concerned, the station should be reestablished without delay and continuously operated, by a neutral organization if necessary.

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